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1. INTRODUCTION

This paper presents the physics relevant to showing that the Drell-Yan process offers the possibility for measuring flavor specific quark momentum distributions of free hadrons and their possible modification in nuclei. The use of this process has been advocated by several authors and some of this previous work will be heavily drawn upon.

There exist useful reviews of the Drell-Yan process, for example an excellent 1982 review[1] by Kenyon and the proceedings of the Fermi Lab Drell-Yan Workshop.[2] However the reader should be aware that the thorough understanding of the process has greatly improved since these reviews were written. The outstanding theoretical problems present in 1982, the K factor and anomalous $p_\perp$ distributions, are now well understood.

One of the stated goals of nuclear physics is a characterization of nuclear behavior based on QCD. Realization of this goal doubtless lies in the distant future as it requires both a quantitative method for dealing with confinement to obtain hadronic structure and characterization of hadronic interactions in terms of quarks and gluons. At the present the development is in two directions; the largest theoretical effort goes into developing models of QCD to yield hadronic structure. Less effort is invested in establishing the interactions necessary to provide the basis for calculations in nuclei. On the experimental front, deep inelastic lepton scattering provides a direct measure of the quark momentum distribution of nucleons, both free and inside nuclei. Studies of hypernuclear structure and hyperon-nucleon scattering provide clues to the underlying mechanisms of hadronic interactions.

The most celebrated case of nuclear medium effects on the quark momentum distribution is the so-called EMC effect.[3] Figure 1 shows the data collected by the EMC group measuring the ratio of the quark structure function per nucleon measured in Fe to that measured in ^2H. While there is some controversy about details of the data there is little doubt that there is a relative dilution of quark momentum in Fe at intermediate values of x ($0.3 \lesssim x \lesssim 0.6$). This observation has produced a spate of theoretical explanations ranging from quark deconfinement within the nucleus to pion exchange currents to a rather trivial explanation based on nuclear binding effects. Whatever the ultimate explanation we take the point of view that measurements of the quark

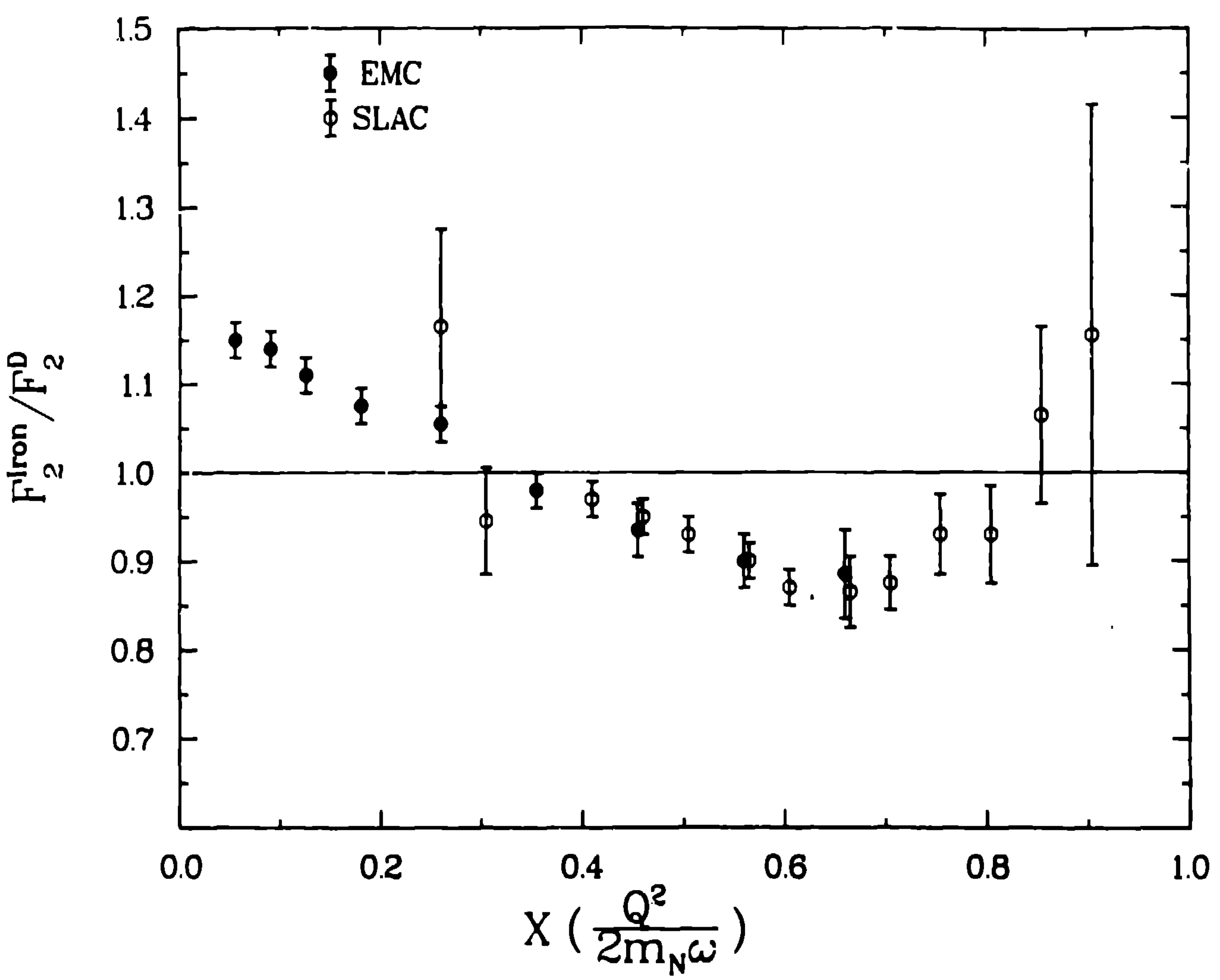

FIGURE 1
Ratio of the quark structure function $F_2(x)$ per nucleon as measured in Fe to that measured in ^2H. The EMC data are from Ref. 3 while the SLAC data are from A. Bodek et al., Phys. Rev. Lett. 50 (1983) 1431, 51 (1983) 534.

distribution functions in nuclei are extremely important from two points of view: First they can tell us if hadronic structure is modified in nuclei (its immutability is an implicit assumption of all detailed models of nuclear structure) and secondly these quark distributions should contain information about the hadronic content of nuclei. It is significant to note that until the EMC experiments there was no measurement capable of addressing the question of whether there were more or less pions in a nucleus than those which "dress" the individual nucleons. In principle the comparison of the antiquark distribution function of a free nucleon compared to that measured in a finite nucleus should address that question. Of course, better EMC data (which are being gathered and should be available over the next two years) and information more specific to quark flavor than is the deep inelastic scattering of charged leptons will be required to provide a sound basis for comparison.

This communication will develop the case for flavor specific measurements via use of the Drell-Yan process. It must be admitted however that measurement of flavor specific quark distributions is a long way from a complete description of a hadron much less a nucleus as two- and three-body quark correlation functions are obviously of great importance. However many crucial issues may in principle be addressed via quark distribution measurements. For example relativistic[4] descriptions of the nucleon-nucleus interaction give rise to a sizable component of N-$\bar{N}$ per nucleon. The enhanced number of virtual pairs may be observable in measurement of the antiquark distribution function. In a similar fashion one should be able to test the prediction of many nuclear models in terms of the enhanced or altered quark distribution function implicit in the model. Much work needs to be done to clarify how to carry out the deconvolution of virtual hadronic components in terms of the quark structure functions. While there exist a few examples[5,6] of such work in the literature there is no general agreement on how these deconvolutions should be carried out.

2. THE DRELL-YAN PROCESS

The discovery by the EMC of an observable difference in the quark distribution function per nucleon between Fe and ^2H generated a great deal of interest among nuclear and particle physicists. It has proven difficult however in the intervening three years to provide a specific explanation for the effect largely because of the very limited information that can be obtained from inclusive deep inelastic scattering of charged leptons. For very large values of the momentum transfer Q the following condition obtains for the scattering from inelastic quarks

$$R = \frac{\sigma_L}{\sigma_T} = \frac{F_2 - 2xF_1}{2xF_1} \approx 0 \quad .$$

In this approximation the cross section for charged lepton scattering is written[7] as

$$\frac{d^2\sigma}{dxdy} = \frac{8\pi\alpha^2 m_p E}{Q^4}\left[\frac{1 + (1 - y)^2}{2} F_2(x)\right] \tag{1}$$

where $y = \frac{E-E'}{E} = \frac{\nu}{E}$ and $x = \frac{Q^2}{2m_p\nu}$. The variable x is to be understood as the fraction of a nucleon's total momentum carried by the struck quark. In terms of quark degrees of freedom the structure function $F_2^{em}(x)$ is

$$F_2^{em}(x) = x \sum_i e_i^2(q_i(x) + \bar{q}_i(x)) \qquad (2)$$

where i is an index denoting the quark flavor and e_i is the charge of the i^{th} flavor. The designation $q_i(x)$ ($\bar{q}_i(x)$) is the probability of finding a quark (antiquark) of flavor i carrying momentum fraction x.

Equation 2 reveals the limited information that can be obtained from deep inelastic charged lepton scattering. The charged leptons scatter from <u>all</u> quarks and antiquarks with a weight fixed by the square of their charge. In order to obtain more specific information on the quark flavor other deep inelastic processes such as charge changing neutrino scattering can be employed. As neutrinos couple to quarks in the same manner as antineutrinos couple to antiquarks the cross sections for neutrino (ν) and antineutrino ($\bar{\nu}$) scattering from an isoscalar nucleon $\left(\frac{p + n}{2}\right)$ can be written as

$$\frac{d^2\sigma^{\nu N}}{dxdy} = \frac{G^2 m_p xE}{\pi}[u(x) + d(x) + 2s(x) + (1 - y)^2(\bar{u}(x) + \bar{d}(x))] \qquad (3a)$$

and compacting notation by writing $u(x) = u$,

$$\frac{d^2\sigma^{\bar{\nu} N}}{dxdy} = \frac{G^2 m_p xE}{\pi}[\bar{u} + \bar{d} + 2\bar{s} + (1 - y)^2(u + d)] \quad . \qquad (3b)$$

Thus in principle, combinations of ν and $\bar{\nu}$ scattering or ν^- scattering at large values of y should yield the antiquark distribution function for the light quarks. Figure 2 shows the results[8] obtained by the CDHS group who measured the ratio of the antiquark distribution functions in Fe and ^1H. The range in x over which the measurement was possible is very small and the errors are quite large. The curves included in Fig. 2 are the predictions[9] of a rescaling model and a pion exchange calculation. Both of these models describe the EMC effect but differ greatly for fundamental reasons on their predictions of the antiquark distributions. Unfortunately the neutrino measurements are not sufficiently sensitive to distinguish between these models and would require a better than tenfold increase in statistics to do so. Hence if progress in this area is to be made other measurements must be brought to bear.

As indicated in the introduction the Drell-Yan process has just the specificity required to provide flavor specific quark or antiquark distribution functions.

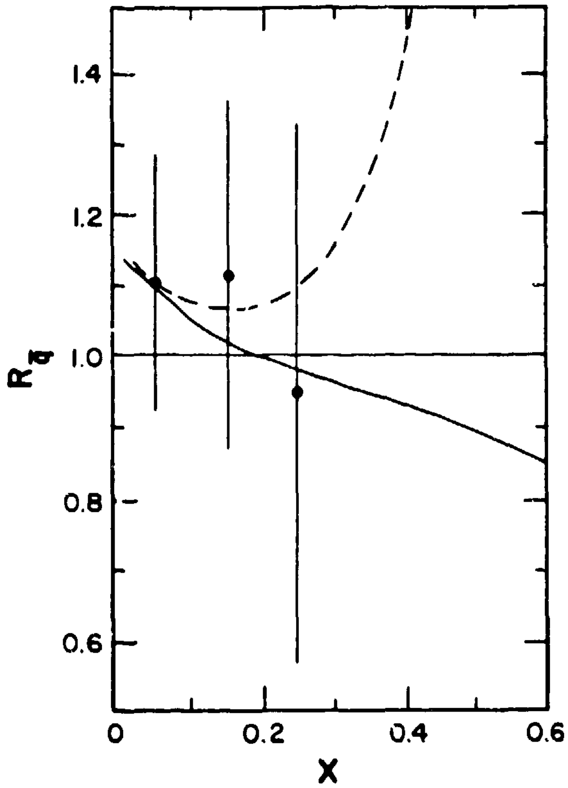

FIGURE 2
Ratio of the antiquark structure functions $\bar{q}(x)$ per nucleon for Fe compared to H. The data are from Ref. 8 while the prediction of the rescaling models (solid curve) and the pion exchange model (dashed curve) come from Ref. 9.

The use of the Drell-Yan process has been advocated by several authors[9-13] to measure quark distribution functions in nuclei. Many[9,10,12,13] advocate its use for measuring the antiquark distributions which if done to sufficiently accuracy could provide entirely new information on QCD effects in nuclei. The Drell-Yan process is shown in Fig. 3. In this process a quark or antiquark from the projectile (1) annihilate with a corresponding antiquark or quark in

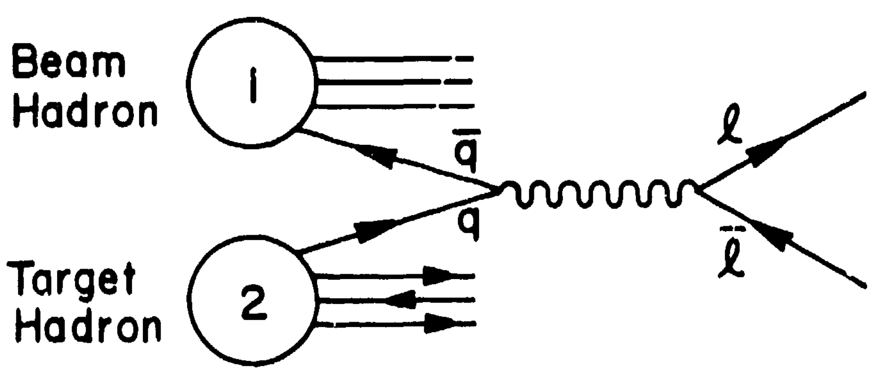

FIGURE 3
Diagram of the Drell-Yan process in which $H(1) + H(2) \rightarrow \ell\bar{\ell}x$.

the target (2) creating a massive photon which decays to a dilepton pair. The expression for the yield of dileptons is given by

$$\frac{d\sigma}{dx_1 dx_2} = \frac{K4\pi\alpha^2}{9sx_1x_2} \sum_i e_i^2[q_i(1)\bar{q}_i(2) + \bar{q}_i(1)q_i(2)] \quad . \qquad (4)$$

The kinematics of the process is simple with the energy of the virtual photon given by

$$E_\gamma = (x_1 + x_2)\frac{\sqrt{s}}{2}$$

with a momentum along the beam direction.

$$p_\ell = (x_1 - x_2)\frac{\sqrt{s}}{2}$$

hence the mass of the virtual photon is

$$m_\gamma^2 = E_\gamma^2 - p_\ell^2 = sx_1x_2$$

where the center of mass energy, s is

$$s \simeq 2m_pE \quad .$$

The basic relation between the physical observables and the quark variables is

$$x_1x_2 = \frac{m_\gamma^2}{s} \equiv \xi$$

and

$$x_1 - x_2 = \frac{2p_\ell}{\sqrt{s}} \equiv x_F \quad .$$

Equation (4) was derived[14] in the simple parton model and in order to achieve agreement with experiment the quantity K had to be set equal to approximately two. Recently several authors[15] have shown tbat the K factor can be calculated within QCD and its constancy and value are well reproduced. In addition the anomalous perpendicular momentum ($p_\perp$) observed for the dilepton pair can also be accounted for via QCD calculation.

Distortion of the quark momentum distribution via initial state interactions represents a possible difficulty for unambiguous measurements in finite nuclei. This problem has been considered by a variety of authors[16,17] who all came to the conclusion that for measurements detecting sufficiently massive dilepton pairs the effects of initial state interactions is small. For example the condition derived by Bodvin[16] et al. is

$$m_\gamma^2 > (0.25\ \text{GeV})A^{2/3} \quad . \tag{5}$$

As will be shown below it is necessary to have $m_\gamma^2 > (4\ \text{GeV})^2$ in order to avoid contributions to the dilepton yield from J/ψ vector mesons. Using that condition in Eq. (5) it is clear that one is quite safe even for the heaviest nuclei.

One test of these notions of distortions is the A dependence of structure function measurements. Figure 4 shows a plot of the results obtained by the

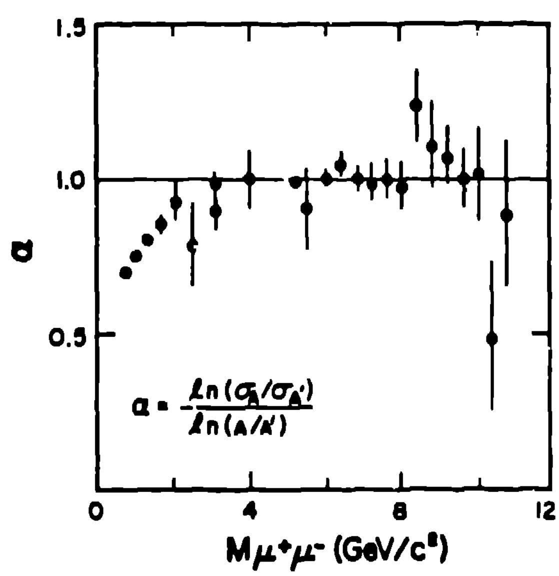

FIGURE 4
Plot of α versus the mass of the dilepton pair.

CBF collaboration.[18] These results show convincingly that the observed yield for $m_\gamma^2 > 4\ \text{GeV/c}^2$

$$d\sigma_{DY}(h\cdot A) = A\, d\sigma(h\cdot N) \quad . \tag{6}$$

A tabulation of all results searching for A dependence is presented in Kenyon's review where it can be seen that Eq. (6) is satisfied to the limit of experimental accuracy (2%).

Fig. 5 is an extensive plot of the yield of $\mu^+\mu^-$ pairs as a function of the mass of the dilepton pair. The measurement is carried out with proton at a laboratory energy of 400 GeV/c. In addition to the continuum yield of Drell-Yan $\mu^+\mu^-$ pairs there are peaks in the observed yield which result from the pair decay of vector mesons (ρ, ω, ψ, ψ', τ, τ', etc.). Obviously measurement of the Drell-Yan process must avoid these contributions, hence a safe region to work is $4 \leq m_{\mu\mu} \leq 8$ GeV/c².

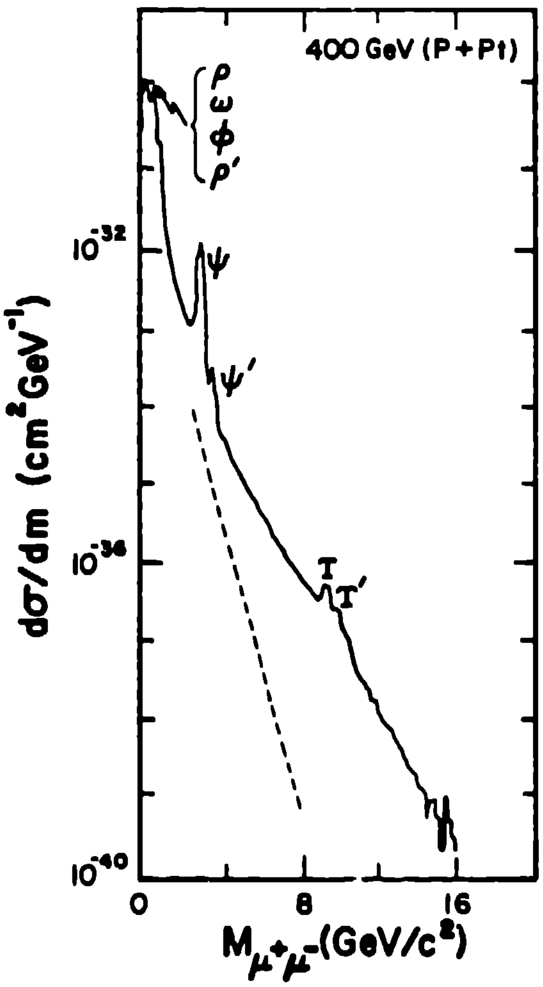

FIGURE 5
Yield of $\mu^+\mu^-$ pairs as a function of $M_{\mu^+\mu^-}$. The data are due to the Columbia-Fermilab-Stonybrook (CFS) collaboration as presented in Ref. 1.

The Drell-Yan model leads to a simple prediction of the angular distribution of the leptons relative to the beam direction in the rest frame of the dilepton pair. In a collision q-$\bar{q}$ annihilation produces a virtual photon with its spin aligned along the beam direction. This leads to an expected angular distribution of the form $1 + \cos^2\theta$. For $m_\gamma > 4$ GeV the measured distributions[19] are as expected. The angular distribution measured for $m_\gamma \approx m_{J/\psi}$ the observed distribution was nearly isotropic. An interesting observation made in Ref. 19 is that the angular distribution observed for $2.0 \lesssim m_\gamma \lesssim 2.7$ GeV is identical to the one predicted for the Drell-Yan process. This window should be very interesting to use to investigate initial state interactions mentioned above that should occur in sufficiently heavy nuclei.

It is interesting to see how data already obtained via the Drell-Yan process compare[20] with the EMC effect. Figure 6 shows the ratio of the Drell-Yan yield for C, Cu, and W. It is shown as a function of x_2. The dotted line is the expected result based on the EMC effect. It is clear that the existing data, while consistent with the EMC effect, are not of sufficient accuracy to cast any light on this interesting subject.

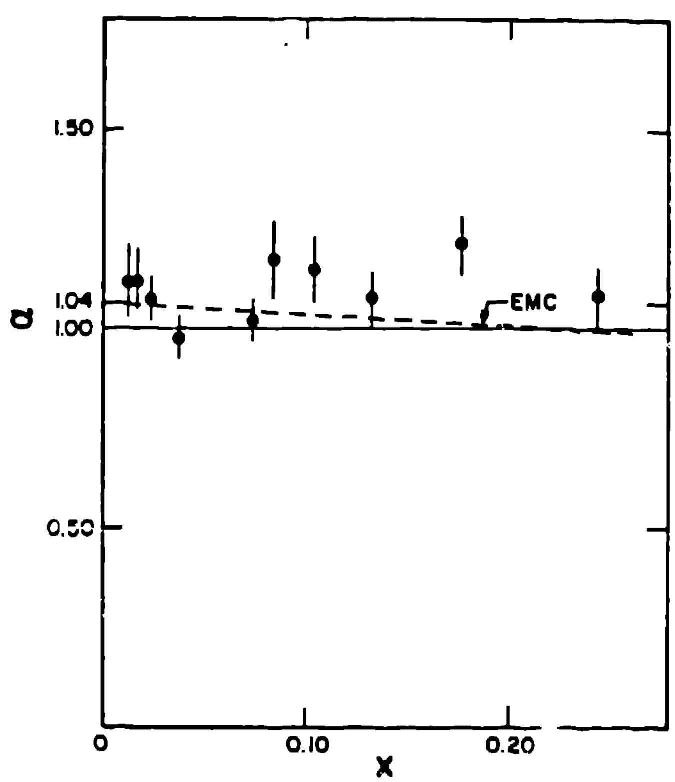

FIGURE 6

Plot of α as a function of x_2. The data are from K. J. Anderson et al., Phys. Rev. Lett. 42 (1979) 944 while the EMC rescaling prediction is from Ref. 20.

Thus it appears that the Drell-Yan process has the capability of yielding accurate information of the nuclear effects on quark momentum distributions. Further the Drell-Yan process can be used much more selectively to yield much more specific information than deep inelastic charged lepton scattering ever can.

3. MEASUREMENT OF THE ANTIQUARK DISTRIBUTION FUNCTION

Let us now address specifically how the antiquark distribution functions in a nucleus would be measured. Figure 7 shows the structure functions $F_2 = x(u + \bar{u} + d + \bar{d} + \frac{4}{5} s)$, $xF_3 = x(u - \bar{u} + d - \bar{d})$, and $\bar{q}^{\nu} = x(\bar{u} + \bar{d} + 2\bar{s})$ as measured for the nucleon. At large values of x, F_3 the valence quark distribution function varies as $(1 - x)^3$ while the antiquark distribution falls like $(1 - x)^8$. Hence in a Drell-Yan experiment where the incident particle is a proton and one selects a sufficiently large value of x_1 (forcing the particle to be a quark), then to arbitrary accuracy the annihilated target particle must be a corresponding antiquark.

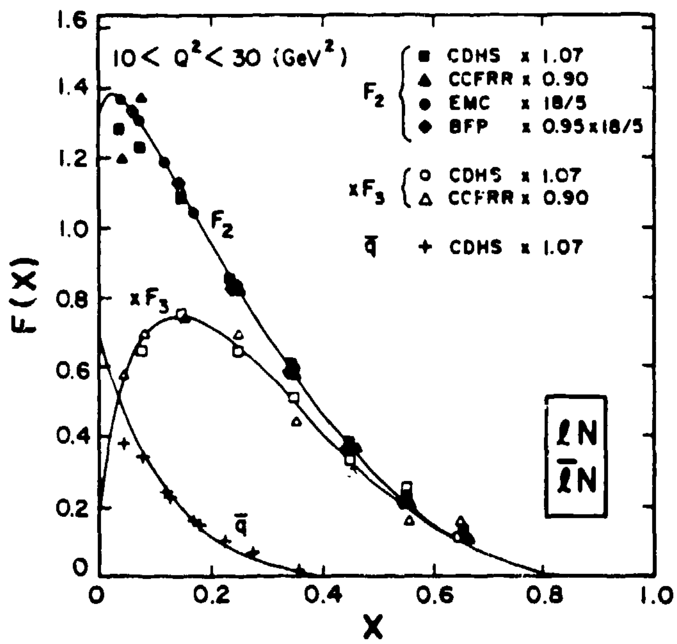

FIGURE 7
The nucleon structure functions F_2, xF_3, and $\bar{q}$ as defined in the text and presented in Ref. 7, p. S61.

Figure 8 shows the kinematic regime in which the antiquark distribution function of the target (x_2) may be measured. In principle the conjugate hatched area permits direct measurement of the quark distribution in the target and to check the observed result against deep inelastic lepton scattering. This is a powerful check against the effect of distortions due to initial state scattering. Figure 8 also shows the range of $x_1 x_2$ accessible with 45 and 30 GeV beams. As the cross sections fall like $(1 - x_2)^{11}$ it is clear that 45 GeV is near the minimum energy one would wish to employ.

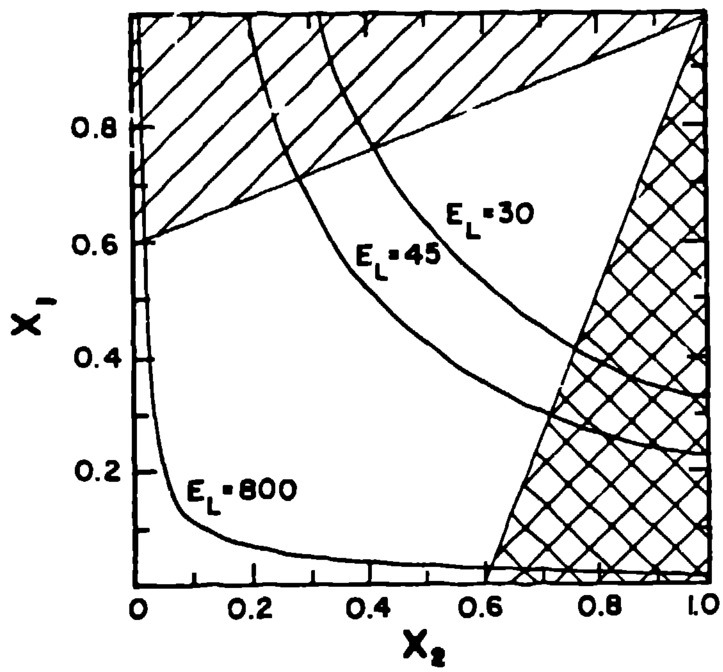

FIGURE 8
The upper limit region allows unambiguous measurement of the antiquark distribution in the target via the Drell-Yan process while the lower cross hatched region yields the quark distribution. The entire area to the right of the curves labeled E_L shows the region of x_1x_2 space accessible with a given laboratory energy in GeV.

Further there is little reason to employ higher energy than necessary to measure the region of x_1x_2 that one wishes to investigate. The reason for this is seen in Eq. (4). Increasing the center of mass energy only reduces the cross section unnecessarily. Of course high energy has to be employed if one wants to investigate the antiquark distribution at small values of x_2 as the mass of the pairs must exceed 4.2 GeV. The minimum value of x_2 that can be investigated is then

$$x_2 > \frac{9.43}{p\ (\mathrm{GeV/c})} \tag{6}$$

where p is the momentum of the incident hadron.

The above discussion shows that in principle that ratio of antiquark distribution function for nuclei can be measured. Figure 9 shows the expected statistical accuracy that could be achieved with a 45 GeV proton beam. One assumes a 4-month run, 10^{13} protons sec^{-1} on a 10% interaction length target of Fe and ^2H and a 10% spectrometer acceptance. New ideas on spectrometer design and ways of handling the incident beam could greatly reduce the required running time. The proposed Los Alamos design for its advanced hadron facility has 20 times the current used in the above consideration. Finding a mode that

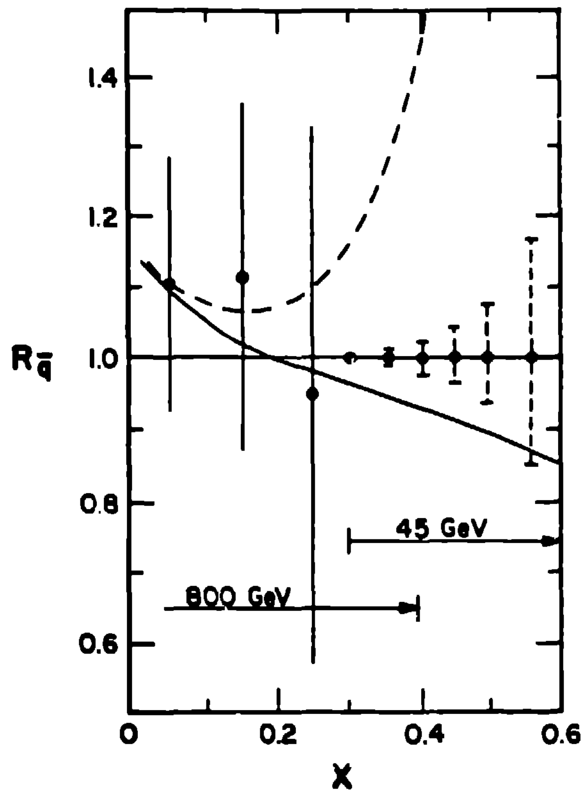

FIGURE 9
Identical to Fig. 2 but indicative of the statistical accuracy with which the ratio of the antiquark distribution factor could be measured under conditions discussed in the text.

would fully utilize this current in Drell-Yan measurements would reduce the required running time to the order of 1 week!

A further feature of Drell-Yan measurements that requires comment is the possibility of examining quark mass effects. For example, in an earlier measurement[21] the ratio of the K^- to π^- structure function on a platinum target was obtained. As shown in Fig. 10 the ratio for the K^- yield divided by the π^- falls appreciably below 1 for $x_1 > 0.7$. The reason proposed for this in Ref. 21 is that at such large values of x_1 only the valence quarks of the mesons ($K^- = |s\bar{u}\rangle$, $\pi^- = |d\bar{u}\rangle$) are relevant. The $\bar{u}$ annihilates on u quarks in the target, hence the reason that the yield from kaons falls below that from pions is the larger mass of the strange quark which causes the $\bar{u}$ in the kaon to carry a smaller fraction of the total momentum. While this may be correct Ref. 21 makes no note of the fact that as x_1 increases x_2 is allowed to become smaller, in fact it reaches values below $x_2 = 0.1$ at which point the sea plays a significant role (see Fig. 7). It is also known that the number of $\bar{d}$ in the sea exceeds the number of $\bar{s}$ so the above explanation based on the mass of the strange quark may not be correct. Drell-Yan measurements with K^+ can provide the fraction of target sea quark contributions to the K yield.

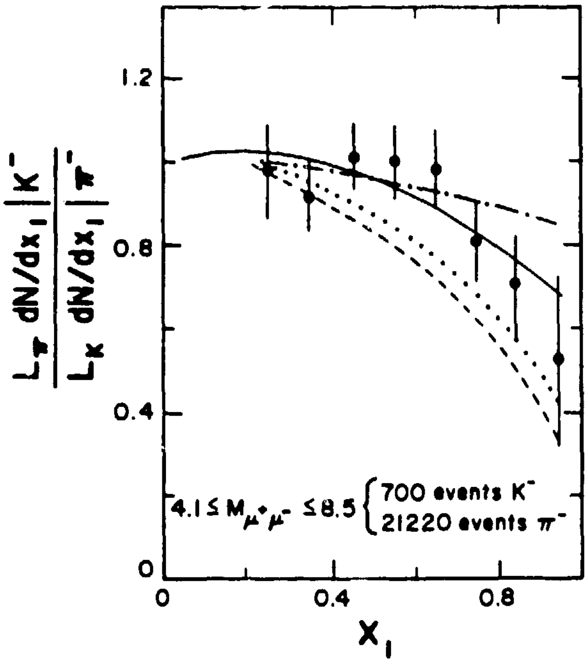

FIGURE 10
Ratio of the structure function of K^- to π^- as measured by Ref. 21.

I believe that we can see an exciting program of flavor specific quark momentum distribution measurements that may represent the best information that physicists will be able to obtain in this area. These measurements should illuminate both hadron structure functions and nuclear medium effects in a unique way. Insofar as this is the case, I believe that it is imperative that the energy of the kaon factories under consideration be increased well above 30 GeV to at least 45 GeV and there is a very good case for going to 60-80 GeV. This important question of the upper energy should be the focus of future meetings and discussions.

I would like to acknowledge useful discussions with Joel Moss, J. C. Peng, and M. Johnson.

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